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US Navy Submarine Sea Trial of NASA developed Multi-Gas Monitor

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During a successful 2 year technology demonstration of the tunable diode laser spectroscopy (TDLS) based Multi-Gas Monitor (MGM) on the International Space Station (ISS), we began discussing with the US Navy the possibility of conducting a sea trial of an MGM on a submarine. The sea trial would also include a gas chromatography/differential mobility spectrometer based Air Quality Monitor (AQM), which is used operationally on ISS for volatile organic compound analysis. AQM preparation and results will be the subject of a separate paper. The Navy's interest in testing NASA equipment in general relates to their ongoing search for better air monitoring technology. NASA's goal is studying submarines as closed environment analogs to spacecraft. MGM's core technology was developed by Vista Photonics Inc using Small Business Innovation Research (SBIR) grants and expanded for various applications using NASA program funding. The MGM measures oxygen, carbon dioxide, ammonia and water vapor in ambient air, displays concentrations with temperature and pressure, and stores 30 second moving averages. The sea trial involves collocating the instrument with the Central Atmosphere Monitoring System (CAMS Mk II) of the submarine, connecting it to rack power prior to departure, and letting it run during the entire 90 day patrol. All data is stored within MGM, with no connection to the vessel data bus. Crew intervention is limited to checking MGM periodically to see that it is working and power cycling if necessary. After the trial is over, the unit with its data will be retrieved. Post sea trial calibration check and data analysis are planned and results will be compared with both CAMS Mk II data and results from MGM's ISS technology demonstration. Since the sea trial itself has been delayed, this paper describes the preparation of MGM for the sea trial and also provides a summary of the latest data from the ISS MGM technology demonstration.

Nomenclature

AQM = Air Quality Monitor
CAMS = Central Atmosphere Monitoring System (Mk II)
ICES = Int'l Conference on Environmental Systems
JEM = Japanese Experiment Module
JSC = Johnson Space Center
MCA = Major Constituents Analyzer
MGM = Multi Gas Monitor
OLGA = Optical Life Gas Analyzer
ppm = parts per million
SBIR = Small Business Innovation Research program
SPHERES = Synchronized Position Hold, Engage, Reorient, Experimental Satellites (internal ISS payload)
TDLS = Tunable Diode Laser Spectroscopy
USB = Universal Serial Bus

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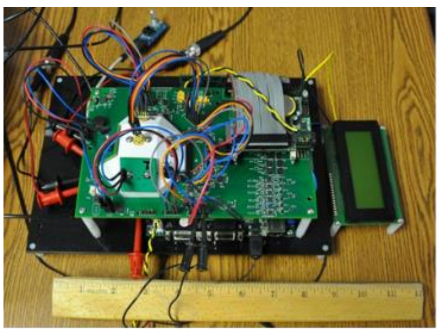
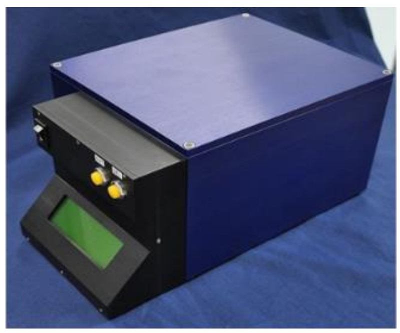
Introduction

At past ICES conferences, we reported on the development, ground testing and flight demonstration of a tunable diode laser spectroscopy (TDLS) based Multi-Gas Monitor (MGM), which measures oxygen (O_2), carbon dioxide (CO_2), ammonia (NH_3) and water (H_2O) vapor[1-2]. The development of the technology traces to Small Business Innovation Research grants to Vista Photonics Inc of Las Cruces, NM. Originally called Optical Life Gas Analyzer (OLGA), the implementation history of MGM is shown pictorially in Figure 1. Each version represents progress in the spectroscopy, hardware, software, data display and packaging. One critical focus was on minimizing power draw, with battery power in mind. Power was reduced to the point that version 3 runs on 3 Canon camcorder batteries (P/N BP-930). The flight technology demonstration version includes an option to run on 5 imbedded lithium ion polymer (pouch) batteries, although primarily operated on 5V USB power in the rack. The final version of MGM is version 2 rebuilt, updated and repackaged into a smaller version 5, with a larger backlit display. This is the version set to undergo a sea trial on a US Navy submarine.



2011 OLGA sensor v1.0



2011 OLGA v2.0 Lab Unit

2012 OLGA v3.0 Ground Demo

2013 Nanoracks MGM Flight v4.0

2015 Blue MGM for sea trials v5.0

Figure 1. Pictorial history of the development of the Multi-Gas Monitor

Details of the technology demonstration of MGM on the International Space Station were previously reported with results of the first year of operation[3]. MGM has spent 3 years operating on ISS. The timeline starting from the point of MGM calibration on the ground before launch to ISS and ending with recent work to return MGM to ground is provided in Table 1. The tech demo proved successful after 6 months, but was extended out to 2 years. Nearly 2 years of data has already been downlinked, analyzed and reported. During this past year (2016), MGM remained installed in Nanoracks and evidently powered on, but no data was downlinked (there was no flight or ground support for the payload since all objectives had been achieved). The return of MGM to Earth will allow the technical team to inspect and test the unit, and potentially retrieve a treasure trove of data from this past (3rd) year of operation. In addition, post flight calibration checks will be conducted for all 4 gases to determine if any drift or aging of the optical cell or lasers has occurred. By the date of ICES 2017, it will be 4 years since the unit was calibrated.

Table 1. Timeline for flight demonstration of the Multi-Gas Monitor (MGM)

Date	Event
Jul 22-30, 2013	MGM calibrated at NASA-JSC
Nov 7, 2013	MGM launched on 37 Soyuz
Feb 3, 2014	Activation and check out
Feb 11, 2014	SPHERES CO_2 thruster unplanned "challenge"
Jul 25, 2014	Ammonia inhalant test conducted by crewmember
Dec 15, 2014	Manual reset by crewmember
Jan 14, 2015	Thermal control ammonia false alarm
Jan 16-17, 2015	SPHERES CO_2 thruster unplanned "challenge"
Aug 25-26, 2015	Deployed on battery power to Node 3
Aug 28-Sep 28, 2015	Deployed on 28V EXPRESS rack power to US Lab
Sep 28, 2015 onward	MGM reinstalled in JEM Nanoracks Frame (Nose out)
Oct 1, 2015 to Jan 1, 2016	Sporadic data takes; MGM display failed late November
Mar 10, 2016	Crew power cycled MGM & photographed display
Jan 19, 2017	Rack/MGM powered off GMT 19 at 14:15
Mar 19, 2017	MGM returns to Earth on SpaceX 10 Dragon capsule
Apr 2017 (planned)	Post flight inspection and data analysis at JSC

Experimental

Analytical and physical specifications of the sea trial version of MGM are listed in Table 2. One of the principle advantages of the technology is the extremely wide dynamic range—2 orders of magnitude or more, if required. The oxygen, carbon dioxide and humidity ranges expected on submarine will be easily covered by the MGM. There are several potential sources of ammonia on submarines including human respiration and the liquid amine CO_2 scrubber. It will be interesting to determine if ammonia ever exceeds MGM's lower detection limit of 5 ppm. Although MGM has quite a small power draw, batteries are not needed or wanted for the sea trial version since A/C line power is readily available. On board memory capacity (2 GB) is more than enough for the 90 day sea trial.

Table 2. Physical and analytical characteristics of the Sea Trial Multi-Gas Monitor

Mass	2.0 kg	
Power	2.6 W*	*Dimensions*
Volume	3.1 L	19.7 x 16.5 x 9.5 cm
Data storage	Internal 2GB compact flash card	

Channel	*Precision*	*Concentration Range*
Ammonia	3 ppm	5 – 20, 000 ppm
Carbon Dioxide	20 ppm	250 – 30,000 ppm
Oxygen	0.05 %	4 – 36%
Water vapor	60 ppm	500 – 50,000 ppm

*AC line power with 6VDC inline adapter. No internal batteries.

An operator's manual was created for the sailors assigned to oversee the sea trial once underway. Their sole duty would be to check the display periodically (~ weekly) to verify it is running. Mitigation if necessary is limited to power cycling via the single button. The photo collage of Figure 2 is from the operator's manual.

Figure 2. Sea trial MGM with power cord/adapter (left). A single button powers it ON/OFF (center). A small 5V fan pulls in air sample into the interior cell where the measurements occur and exhausts at outlet. The display (right) reflects the concentrations, temperature, pressure and Nitrogen (N_2) by difference, assuming cabin atmospheric Argon at 0.9%.

Sea Trial Planning

The US Navy is pursuing an at-sea trial of the MGM for two purposes. First, the Navy has continuing interest in evaluating new analyzer technologies with the potential for improving atmospheric monitoring capabilities. Secondly, the US Navy is also investigating the use of a distributed atmosphere monitoring system as a primary submarine atmospheric analyzer. The distributed system would utilize a variety of sensors positioned in selected locations to monitor for life gases (O_2, CO_2, etc.) and trace contaminant gases (CO, refrigerants and other volatile organic compounds) continuously in real time. The MGM, AQM, and the technologies they utilize offer potential improvements to atmospheric monitoring currently utilized on submarines, as well as proven analyzers for use as part of a distributed atmosphere monitoring system. Some of these potential improvements include lower limits of detection, the monitoring of additional atmospheric compounds and improved supportability, maintainability and endurance. A significant advantage to utilizing these NASA-developed analyzers is that they have both operated on ISS, which means proper operation of both analyzers has been validated after exposure to the physical stresses associated with transiting to ISS, in additional to operating for an extended period of time with minimal adjustments required. This provides additional confidence to the Navy due to their successful operational history in a relevant environment to that of a submarine. The planned at-sea trial onboard a US Navy submarine will further document performance in an operational submarine environment.

Performing an at-sea trial of a land-based analyzer has proven to be a successful path to transition a submarine atmosphere monitor. In 2007, the US Navy conducted an 80-day trial of an atmosphere analyzer developed as part of a Navy-sponsored SBIR onboard USS Kentucky (SSBN 737)[4]. This trial confirmed the successful shipboard operation of an optics-based analyzer, and ultimately resulted in the development of a new submarine atmospheric analyzer. In the 2007 at-sea trial, the analyzer of interest was collocated in a shipboard locker next to the CAMS Mk II cabinet, as shown in Figure 3, with a flexible line transporting an air sample from the CAMS Mk II outlet to the analyzer under test. The planned approach is expected to be similar for the current trial, however due to a difference in sampling techniques; the MGM may be placed at the normal CAMS Mk II sampling location, to ensure that data recorded from the CAMS Mk II can be utilized for comparison purposes. As stated previously, the intention is to allow the MGM to operate continuously throughout the trial with minimal action required from the crew.

Figure 3. Nuclear powered Ballistic Missile Submarines the USS Henry M. Jackson (upper left) and the USS Alaska (lower left) with a typical Central Atmosphere Monitoring System (CAMS Mk II) rack mounted in the fan room. This is a potential location for MGM during the sea trial. Photo source: www.navy.mil

Results & Discussion

As of this writing, the sea trial of the blue MGM has not yet occurred. Also, the MGM has just returned (3/19/17) from ISS on SpaceX 10 Dragon capsule, so the final data recovery (Year 3) from the technology demonstration has also not yet occurred. Thus, the data presented here is Year 2 of the ISS MGM technology demonstration for comparison purposes. MGM data for O_2 and CO_2 are compared with the central Major Constituents Analyzer (MCA) on ISS, which draws air from various modules including the Japanese Experiment Module (JEM) where MGM resided. This data along with any Year 3 data recovered from the ISS MGM will be compared with the sea trial results, which will also be compared more directly with CAMS Mk II data from the submarine. For the majority of the 3 year stay on ISS, MGM was installed in a rack as shown in Figure 4 and powered via USB cables connected to the Frame. Gas concentrations and housekeeping data were downlinked roughly weekly at first then became more sporadic. Compressed files were received and analyzed at Johnson Space Center and Vista Photonics. Data trend plots for each gas were updated as often as new data was received. Example data for each gas follows with some discussion.

Figure 4. MGM being reinstalled in Nanoracks Frame in the ISS Japanese Experiment Module

Oxygen

MGM's oxygen data (blue points) for 2015 are presented in Figure 5 along with the ISS Major Constituents Analyzer (MCA) results for JEM module. Gaps in the data set were due to USB connectivity issues, not the MGM itself. Note the 2 sets of data compare very well. MGM has the advantage of not needing the periodic recalibration that MCA requires.

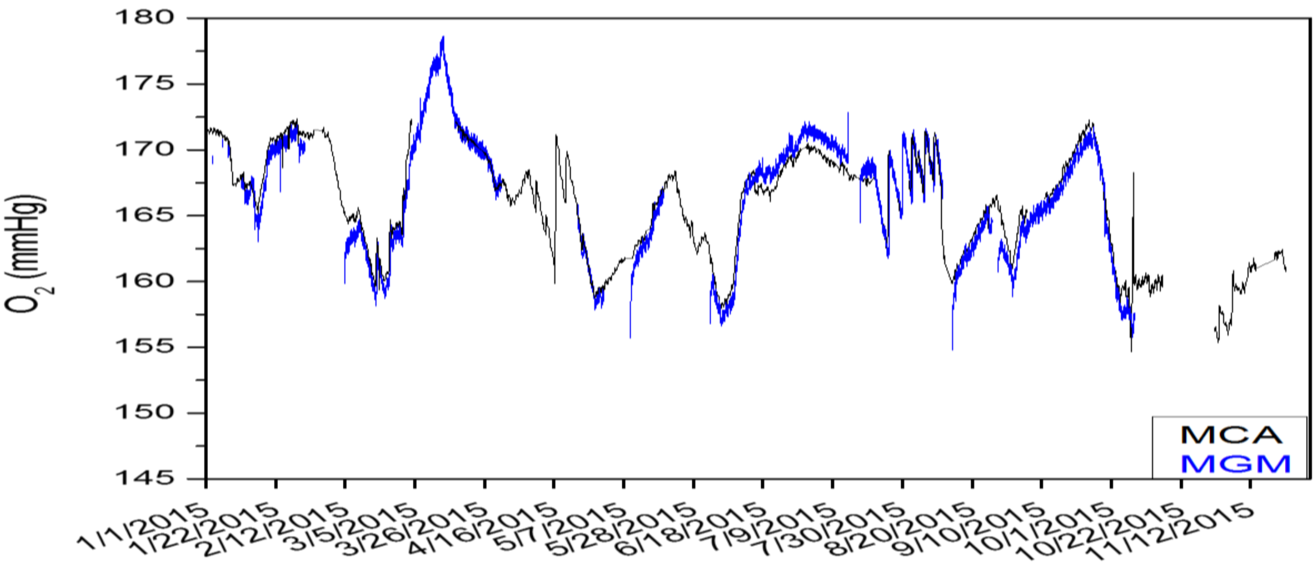


Figure 5. ISS oxygen data from MGM and MCA

Carbon Dioxide

MGM's CO_2 data for 2015 is presented in Figure 6 alongside MCA data for JEM. The 2 sets also track each other very well. Figure 7 is a zoomed in region of Figure 6, showing the diurnal fluctuations in CO_2 concentration, and about a 1 month interval where CO_2 concentrations were intentionally kept well below operational requirements.

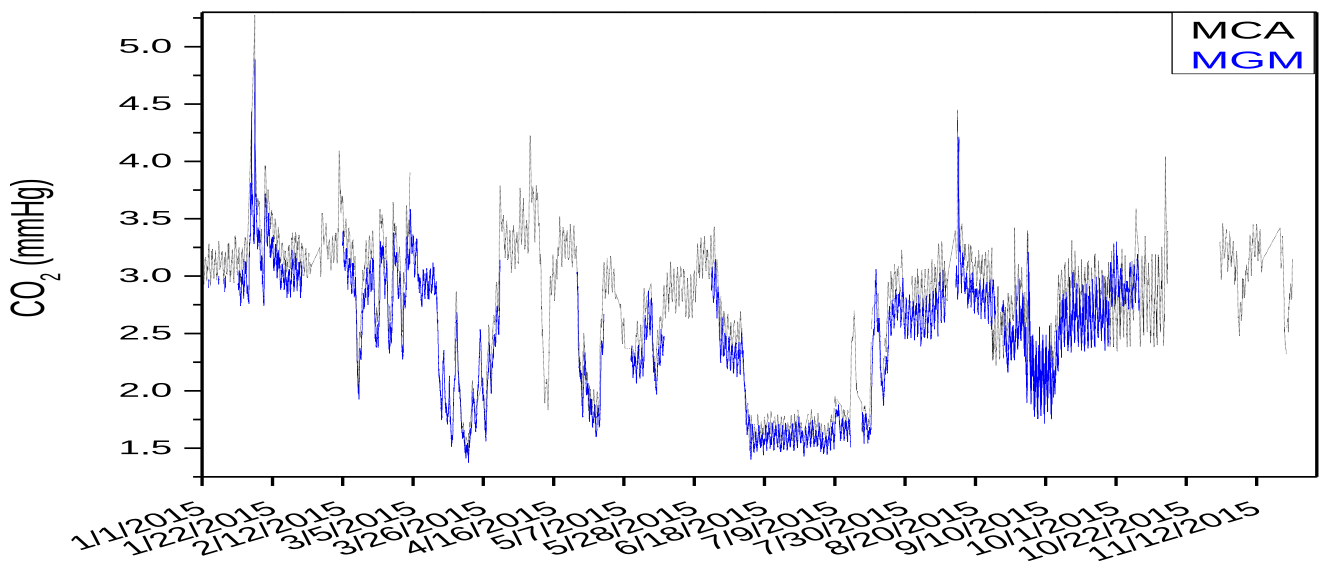


Figure 6. CO_2 results in mmHg partial pressure from MGM compared to MCA.

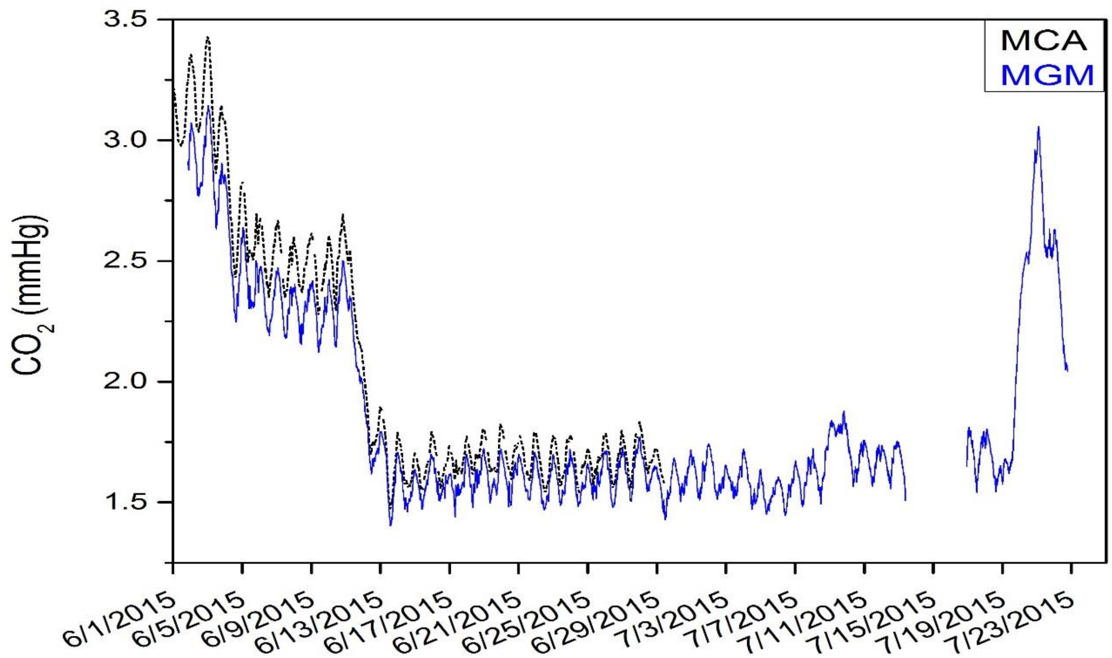


Figure 7. Region clearly showing the day/night cycles in CO_2 concentration.

Humidity

The MGM makes direct measurements of water vapor in ppm. On ISS, there is no real "gold standard" measurement of humidity to compare against MGM, but there are experimental relative humidity sensors in the JEM and Columbus. Except for occasional spikes, MGM found water vapor to be fairly constant ~12,000 ppm in the ISS in a comfortable, habitable range corresponding to about 38% relative humidity. Figure 8 shows the data for the last year of MGM operation. Each of the spikes in water vapor correspond to dry out cycling of the JEM condensing heat exchangers, a regular part of maintenance.

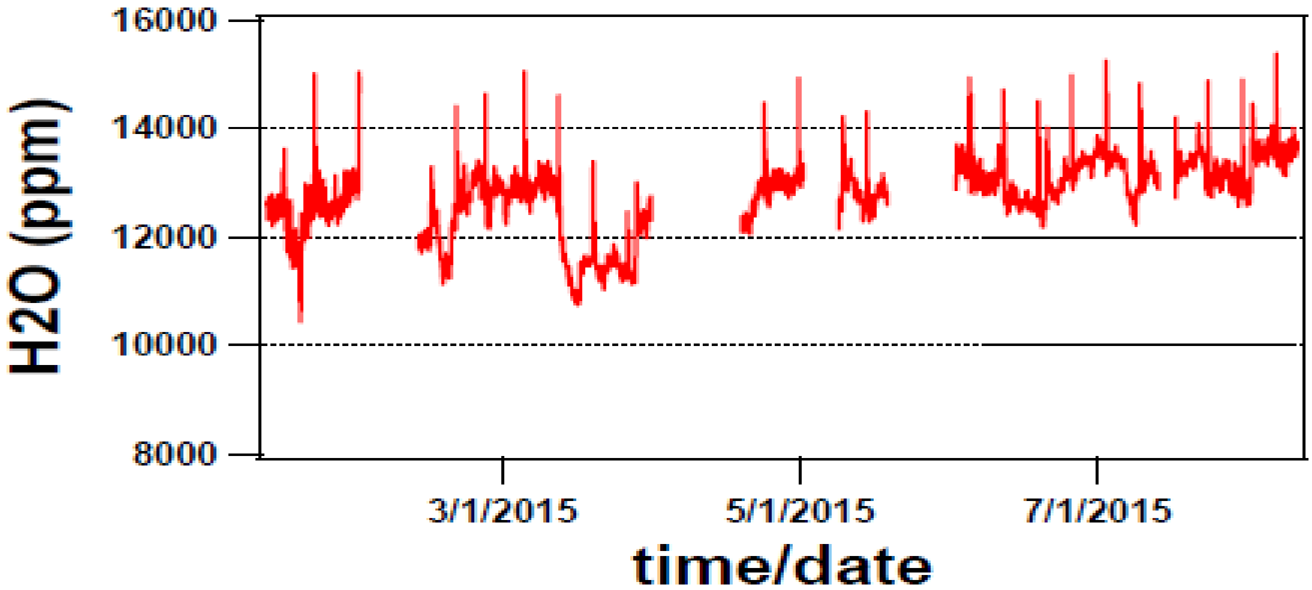


Figure 8. Water vapor measured by MGM is fairly constant around 12,000 ppm. The spikes are attributed to dry out cycling of the JEM condensing heat exchangers.

<u>Ammonia</u>

Normally, ammonia in the ISS atmosphere is low and well controlled. The primary source is the crew. However, there is a small potential for a leak from the external high pressure ammonia thermal control system into the internal water cooling loops and out into the cabin. Hence the interest in monitoring ammonia. Gaps in the plots are from interface issues with the rack frame. Except for a brief test of the ammonia channel by the crew using an inhalant in 2014, MGM did not detect ammonia above ~ 5 ppm baseline noise as shown in Figure 9.

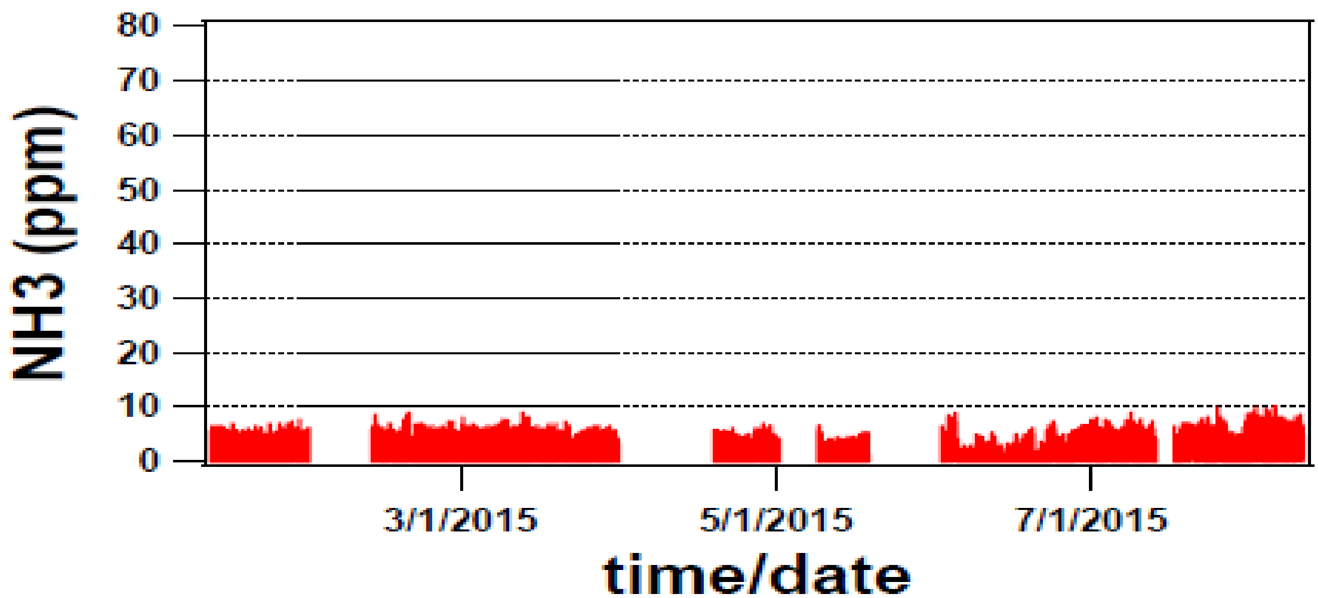


Figure 9. Ammonia as measured by MGM is normally always < 5 ppm, which is the formal low detection limit.

The last set of MGM data from the ISS MGM was downlinked in January 2016 at the point that ground and flight operations support for the MGM tech demo was essentially terminated. We had been getting sporadic data down due to intermittent USB connectivity issues with the Frame. The plots of Figure 10 show nominal levels of O_2, CO_2, water vapor, and cabin atmospheric pressure around a nominal ~ 750 Torr (750 mm Hg). The temperature displayed (~ 29C) is internal MGM temperature which is about 5C warmer than the ambient cabin. The solid line in each graph represents gaps in the data sets.

Conclusions & Future Directions

The Multi-Gas Monitor's core tunable diode laser spectroscopy (TDLS) technology was demonstrated on International Space Station to be rock solid, with a calibration interval longer than 3 years and accuracy that rivals any of the current instrumentation. We anticipate the MGM sea trial data when compared with CAMS Mk II results will show similar results. We anticipate interesting and perhaps similar comparisons between the closed environment of a submarine and that of a spacecraft. Beyond life gases, TDLS is being expanded to cover combustion products including carbon monoxide, hydrogen cyanide, hydrogen chloride and hydrogen fluoride for a total of 8 gases in an enclosure of the same footprint and low power draw as MGM for a battery powered configuration. The future for TDLS based hand held life gas and emergency gas monitors in spacecraft and submarines looks very bright indeed.

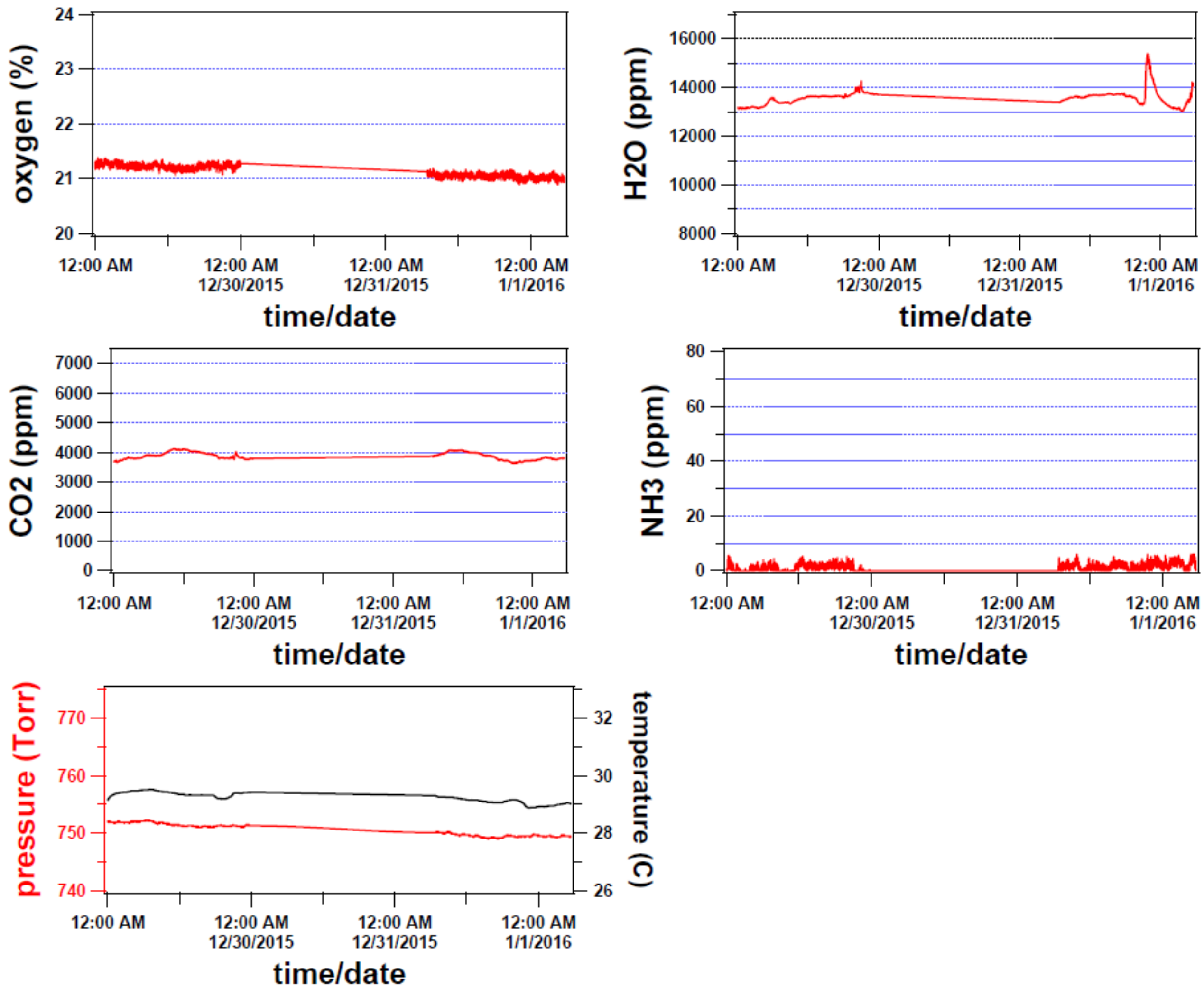


Figure 10. The very last days of MGM data downlinked from ISS on January 1, 2016.

References

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